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An experimentally validated method for temperature prediction during cyclic operation of a Li-ion cell

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ABSTRACT

Li-ion batteries are used widely for electrochemical energy storage and conversion. Heat generation during the operation of a Li-ion cell results in large temperature rise, particularly at high discharge rates. Accurate prediction of temperature rise during operation is a key technical challenge that directly affects both performance and safety. Li-ion cells are often used in cyclic charge/discharge manner, making this a particularly important process to study. This paper presents an experimentally-validated analytical method to rapidly and accurately predict the temperature field in a Li-ion cell undergoing cyclic charge and discharge. Based on recursive solution of the governing energy equation during the cyclic process, this method computes temperature around 16X faster than finite-element simulations, and is found to be in very good agreement with experimental data for over fifty cycles of high-rate cycling of 18650 Li-ion cells. Results indicate that heat loss through the metal foil that provides electrical interconnection is a critical process that governs overall thermal behavior of the cell. A novel technique based on determining the effective heat transfer coefficient of the interconnection is described, which is shown to agree very well with experimental data. Results from this paper may be helpful for design of Li-ion cell systems, as well as real-time temperature prediction and performance optimization.

1. Introduction

Li-ion cells are used widely in energy conversion and storage devices due to excellent energy storage and power characteristics [1–3]. However, heat generation due to Ohmic and non-Ohmic mechanisms [4–7] during the operation of a Li-ion cell is a serious technological challenge [8,9]. It is well known that elevated temperatures dramatically reduce battery lifetime [9]. Even at temperature as low as 80 °C, degenerative processes begin to occur in a Li-ion cell, which cause severe safety issues and lead to thermal runaway [10]. Thus, the dissipation of generated heat through the cell material and into the ambient is an important transport process [8,9]. Impedance to thermal transport through various material interfaces in the cell [11,12] results in large temperature rise [13,14], which not only reduces electrochemical performance, but also leads to safety problems [15–17]. Such problems have been responsible for several recent, well-publicized events of thermal runaway and fire in batteries in automobiles, aircraft and consumer electronic devices.

It is critical to develop thermal management approaches for reducing temperature rise in a Li-ion cell [8,17]. This has been accomplished in the past through external mechanisms, such as the flow of a coolant over the outer surface of the cell [18], embedding the cell in a phase change material [19], the use of heat pipes [20], etc. Some limited work has also been carried out for internal cooling of a cell, for example by heat pipe insertion [21], by using current collector as a heat spreader [22] or by recirculating electrolyte [23] that acts as a coolant. In each case, it is important to accurately determine the cell temperature since it will govern whether thermal management is needed or not, and if so, the extent needed. Ideally, a temperature sensor must be present inside the cell to measure and report the cell temperature, which can be used for active control of thermal management. However, it is not always possible to embed temperature sensors within. Only a limited amount of work exists on internal temperature measurement of a Li-ion cell [24–29]. Due to these experimental limitations, the accurate prediction of temperature rise through mathematical modeling tools is critical. Such thermal prediction tools can play a key role in thermal management of cells, since accurate knowledge of the temperature rise in a cell can be used for proactive cooling of the cell. For example, a prediction of imminent temperature rise can be used for modulating the thermal

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management system, or in an extreme case, completely shut down a cell to prevent thermal runaway. Temperature prediction is also critical for performance optimization, both at the design stage, as well as at run-time. For example, such tools can be used for evaluating and optimizing the thermal performance of a cell. During actual operation of a cell or a battery pack, accurate prediction of temperature rise can be a critical tool for performance optimization strategies such as load balancing.

Like in any other energy conversion system involving heat transfer, there are two distinct approaches for developing predictive tools for temperature rise in Li-ion cells. Finite-element simulation tools can be used for thermally modeling the operation of a Li-ion cell and numerically solving the governing energy equations along with appropriate boundary conditions to determine the temperature field in the Li-ion cell. A significant amount of literature already exists on such approaches [17]. On the other hand, an analytical approach can also be used where possible to derive an exact solution for the governing energy equation, resulting in an exact expression for the temperature rise. A limited amount of literature exists on the use of analytical methods for predicting temperature rise in Li-ion cells [13,14,30,31]. Both steady state and transient methods have been used on cylindrical as well as prismatic cells. Simulations are sometimes preferred due to the flexibility in geometry, thermal properties, etc. However, analytical methods have the advantage of being more accurate and faster to compute compared to numerical simulations. Further, in the context of Li-ion cells, analytical solutions may be preferable for implementation in battery management systems because these can be directly implemented and computed on a microprocessor instead of having to interface with a separate finite-element simulation code, which is often expensive, requires extensive computational power and is in general difficult to interface in real-time.

Cyclic charge and discharge of a Li-ion cell is of specific interest because it models the operation of the Li-ion cell in several realistic scenarios. Heat generation rate during a charge/discharge process is a key parameter that may govern temperature rise. Past measurements show that heat generation rate is a strong function of the discharge rate [7,12]. Key questions to address through the thermal modeling of a cyclic charge and discharge process include the effect of thermal properties and ambient thermal conditions on the temperature distribution in the cell, the effect of rest periods between successive discharges, and the role of electrical interconnection such as metal tabs on the cooling of the cell. The latter is a particularly important factor that has not been investigated much in the past. Since the metal tab or foil that electrically connects the cell to the power source and load usually has high thermal conductivity, its role in determining the temperature distribution of the cell is important to investigate.

This paper presents experimental measurement of temperature rise in a cylindrical 18650 cell during multiple successive cycles of charge and high-rate discharge, and a theoretical heat transfer model that accurately predicts the temperature rise under such conditions. The theoretical model accounts for thermal conduction within the cell, convection to the outside, as well as heat loss through the metal tabs connected to the cell poles. It is shown that heat loss through the metal tabs plays a critical role in determining the thermal behavior of the cell, and a novel technique to accurately account for this effect is discussed. These results demonstrate the capability of real-time computation of temperature distribution in the cell as a function of its electrochemical performance. This analytical approach is around 16X faster than finite-element simulations and offers the capability of close integration with electrical control components of a battery management system.

2. Experimental measurements

Commercially available high power Nickel Manganese Cobalt Oxide Li-ion cells of type INR18650-15L from Samsung are used for experimental measurements. The cells have a nominal capacity of 1500 mAh and internal resistance of 29.0 mΩ (±0.5 mΩ). Electrical connections are made via 0.3 mm thick Ni-coated steel foils welded to the poles. Prior to the measurements, the steel foil is soldered to a 1 mm thick copper plate. For the cycling tests, five cells are connected in parallel via screws to a 5 mm thick copper bar and placed in a temperature-controlled climate chamber (VC7034, Vötsch, Germany) maintained at 25 °C. Fig. 1(a) shows a picture of the prepared Li-ion cell. Fig. 1(b) shows a picture of the test environment. All cycling is conducted using a Maccor Series 4000 cell cycler. The five-cell string is charged initially with constant current of 7.5 A (1C) until voltage of 4.2 V is reached and then the voltage is kept constant until the current reaches 0.1 A. The constant voltage charging is followed by 10 min open circuit step. The discharge is performed with 52.5 A (7C) to a cut off voltage of 2.5 V with a subsequent open circuit step for 10 min. This sequence is repeated for 50 cycles. The temperature of each cell is monitored throughout the process using a Pt-100 temperature sensor attached to one of the cell poles. The sensor is configured in a four-wire circuit for improved measurement accuracy. The obtained temperature profiles as functions of time are used to validate the theoretical model.

3. Theoretical modeling

Consider a cylindrical, axisymmetric Li-ion cell of radius R, height H, mass density ρ and heat capacity C_p as shown in Fig. 1(c). Assume the thermal conductivity of the cell to be orthotropic [32], with k_r and k_z as the radial and axial thermal conductivities respectively. The cell undergoes a cyclic charge/discharge process during which the temperature field within the cell as a function of time is of interest. In order to determine the temperature distribution, the cyclic process is split into N stages that occur in sequence. Each stage is characterized by a fixed heat generation rate Q_i, $i = 1, 2, \ldots N$. The duration of each stage is between $t_i = 0$ and $t_i = t_{F,i}$, where $t_{F,i}$ is the final time of the i^{th} stage. The cell is convectively cooled on the outside surfaces, which is modeled with convective heat transfer coefficients $h_{r,i}$ and $h_{z,i}$ applied on the curved surface, and top/bottom surfaces respectively. These coefficients may vary from one stage to another in order to model changes in convective cooling conditions between charge, discharge and rest stages.

The problem of determining the transient temperature distribution during the charge/discharge process may be solved in a recursive fashion by splitting the temperature distribution into temperature distributions during each stage, $T_i(r,z,t_i)$, so that the temperature field during the i^{th} stage is determined based on the temperature distribution at the end of the previous, $(i-1)^{th}$ stage.

Based on the problem description above, the transient temperature distribution in the Li-ion cell during the i^{th} stage is governed by the following energy conservation equation:

$$\frac{k_r}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_i}{\partial r}\right) + k_z\frac{\partial^2 T_i}{\partial z^2} + Q_i = \rho C_p \frac{\partial T_i}{\partial t_i} \tag{1}$$

Boundary conditions for this problem are as follows:

$$\frac{\partial T_i}{\partial r} = 0 \quad \text{at } r = 0 \tag{2}$$

$$k_r\left(\frac{\partial T_i}{\partial r}\right) = h_{r,i} \cdot T_i \quad \text{at } r = R \tag{3}$$